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Implementation of A Solar PVT Assisted HVAC system with PCM energy storage on a Net-Zero Energy Retrofitted House

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Abstract

This paper presents the functionality and optimization methodology of a novel solar assisted HVAC system developed for the Team UOW Solar Decathlon house, the overall winner of the Solar Decathlon China 2013 competition. This novel HVAC system consists of an air based photovoltaic-thermal (PVT) system and a phase change material (PCM) thermal storage unit integrated with a ducted system with a reverse-cycle heat pump. The system has been designed for operation during both winter and summer, using daytime solar radiation and night sky radiative cooling to enhance the energy efficiency of the air-conditioning system. The PVT system can exchange heat with the PCM thermal storage unit, and the stored heat can be used to condition the space or precondition the air before entering the air handling unit (AHU). This system is controlled by a residential type building management and control system (BMCS). The performance of the system is simulated under various operational modes together with the key controlled variables. The simulation results over two typical months are presented.

1. Introduction

Team UOW (University of Wollongong) was the first team in the history of Solar Decathlon to demonstrate how to upgrade and retrofit an existing building rather than designing a new building from scratch. One of the key targets in this retrofit project was to achieve net-zero energy consumption. To achieve this target, increasing the energy efficiency of Heating, Ventilation and Air Conditioning (HVAC) system is essential [1,2]. Increasing the energy efficiency of various solar assisted HVAC systems with and without thermal energy storage systems has been investigated [3-6]. In particular, thermal energy storage has been considered as an important alternative to solve the problem of mismatch between the energy generation and the building demand, when solar energy systems are implemented in buildings [7].

Thermal energy storage can be categorized according to the type of materials used to store the energy, dependent on that latent or sensible heat is used to store the energy or the methodology used to store the energy in the storage medium [8]. Latent heat thermal energy storage is attractive to researchers because of its high storage capacity per unit of volume or mass, and the fact that the temperature remains almost constant during the phase change process. Compared to sensible heat storage, latent heat thermal storage usually requires less space which can lead to cost savings. The use of active storage to improve the efficiency of HVAC systems has been proven to be effective by the experience gained in different applications [9].

This paper presents the implementation of a solar assisted HVAC system with integrated PVT system, in which a phase change material (PCM) thermal energy storage is used to temporarily store the heat collected from the PVT system and then used later for air-conditioning.

2. HVAC system description

Figure 1 presents the Team UOW Solar Decathlon house and its innovative solar PVT assisted HVAC system. The air delivery system of the house is based on a combination of flexible and rigid ductwork, which allows an effective functional integration of the different "energy components" of the system.

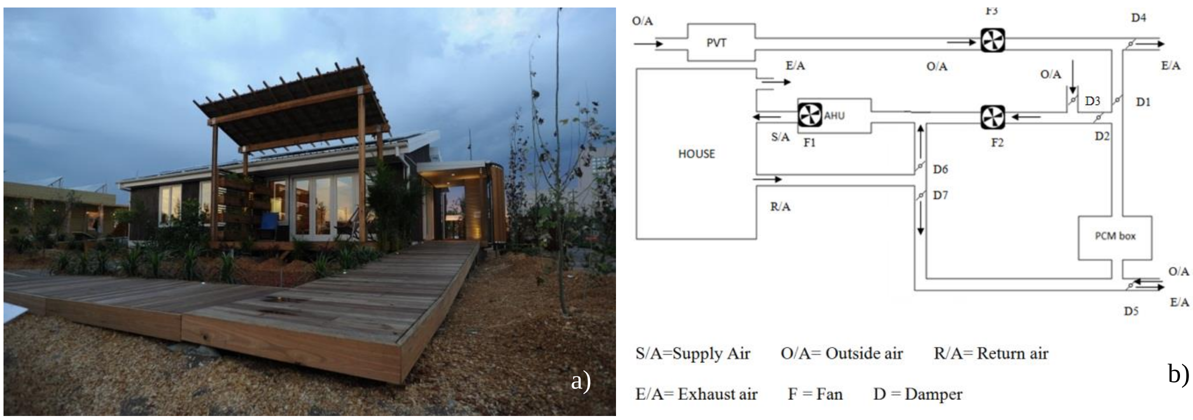


Figure 1: a) Team UOW Solar Decathlon house and b) HVAC schematic.

This HVAC system integrates the different components using a ducted air distribution system, in which variable speed fans are used to control the air flow rate and dampers are used to change and regulate the airflow paths in and out of the system. The use of air in the PVT collector as a working fluid has been dictated by the need of the system to be simply retrofitted to an existing house, with low maintenance requirements and simple integration with a ducted air-conditioning system. The PVT collector is formed by the flexible thin-film CIGS PV panels glued to a metal flashing that bridges the 'valleys' of the roof sheeting. Air can therefore flow in the duct between the underside of the PV panels/flashing and the roof sheeting and exchange heat with the panels. The thermal generation of the PVT has generally, considering Sydney weather conditions, a significant offset with the demand of the building. For this reason an active thermal storage unit has been included in the design of the HVAC system, and a PCM with the melting temperature of 22˚C was selected as the storage material. The PCM at this temperature will pre-heat or pre-cool the air for a standard reverse-cycle air conditioning system with an outdoor condensing unit and an indoor air handling unit (AHU) integrated into the system, to ensure good thermal conditions in the indoor space. The whole system is controlled through a residential type of BMCS with a programmable logic controller developed using off the shelf products and customized logic.

3. HVAC system operating modes

Figure 2 shows the various operational modes of this innovative HVAC system, including three different Conditioning modes and two PVT modes.

3.1. Conditioning modes

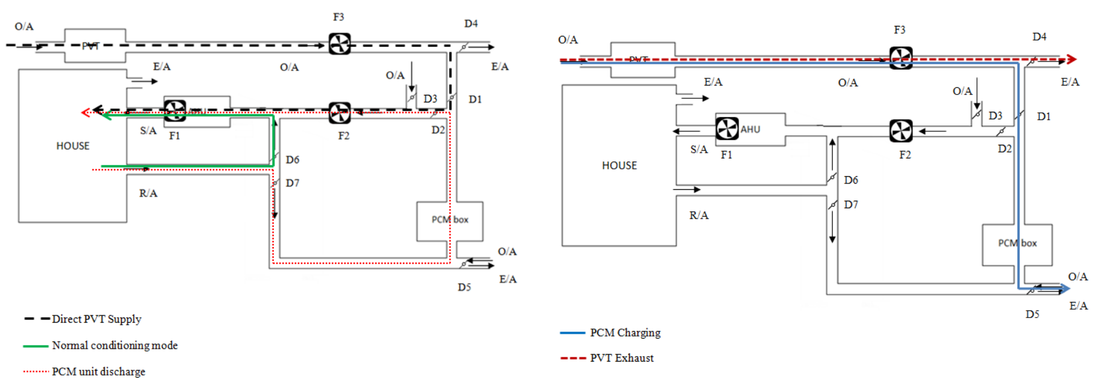
Depending on the indoor conditions, the system can either work in natural ventilation mode through automatically controlling the opening of high level windows, or work in forced mechanical heating and cooling mode. In the mechanical heating and cooling mode, the system can operate in three different sub-modes:

- Direct Photovoltaic-Thermal Supply. If the generation of heating during daytime or cooling during night time (night sky radiative cooling) occurs at the same time as the demand, the heated/cooled air from the PVT system is then directed into the house until the demand is matched. If the demand is higher than the energy extracted from the PVT system, the AHU will cover the remaining heating/cooling requirement.
- Supply Air Preconditioned Through Phase Change Material. In this case, if thermal energy is available in the PCM storage unit the mixture of return air and fresh air will be preconditioned by the PCM, increasing or decreasing the supply air temperature. If the demand is higher than the energy extracted from the PCM storage unit, the AHU will cover the remaining heating/cooling requirement.
- Normal Heating and Cooling Mode. If there are no PVT thermal generation and no thermal energy stored in the PCM, the AHU will supply the required heating or cooling.

3.2. PVT modes

If there is no interfering operating mode activated, the system can operate in two other modes (see Figure 2b).

- PCM Charging. If there is no demand from the house and the PCM unit is not fully charged the PVT system will charge the PCM unit.
- PVT Exhaust. In case there is no heating demand and PCM is fully charged, if the increase in electrical generation of the solar panels due to their temperature decrease is higher than the energy used by the fan, the air can be drawn underneath the PV panels and exhausted directly to ambient.



(a) **Conditioning modes** **(b) PVT modes**

Figure 2: Operation modes of the HVAC system.

4. System integration and control

Figure 3 presents the Solar Decathlon House BMS and Interface. The system is controlled with two different levels, i.e. low level control and high level control. The low level Clipsal C-Bus control system is used to monitor the temperatures, air flow rates, energy consumption and current indoor and outdoor conditions, and control the on/off of dampers and variable position dampers actuators, variable speed drives of fans, windows and lights relays and dimmers. The high level controller (Tridium JACE-6) is completely integrated with the C-Bus system to make the decisions on which mode the system should operate. It also logs all data points with a five minutes sample period.

The JACE controller also integrates the high level controller of the reverse-cycle air conditioning unit using a Modbus gateway that allows the logic to dynamically change the air conditioning mode, temperature set point and fan speed.

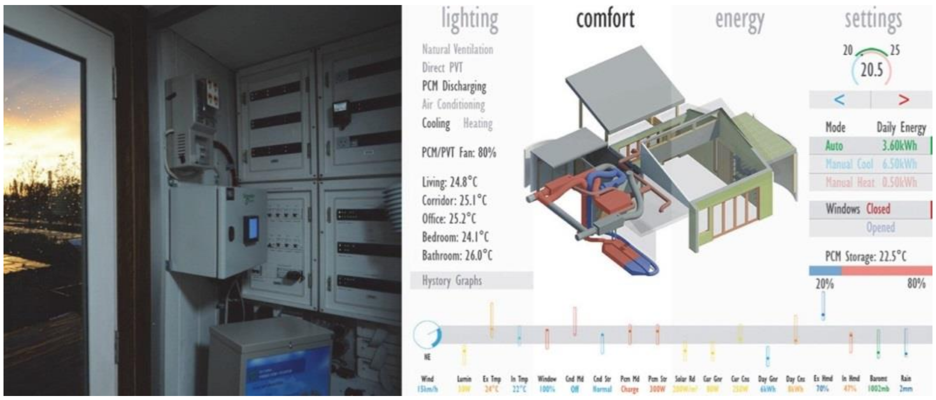


Figure 4: Team UOW Solar Decathlon House BMS and Interface.

The JACE controller data points are also integrated with Matlab using an oBIX (Open Building Information Exchange) Network that allows a Matlab controller to override the logic embedded in the JACE. This allows the implementation of virtually any type of control strategies on the house systems.

5. Simulation and performance analysis

In this section, the performance of the proposed HVAC system is simulated under winter and summer operating conditions. The weather data used is Sydney IWEC weather data. The sampling time of the weather data used for the simulations is 1 hour.

5.1. House thermal demand modelling and HVAC system modelling

The heating and cooling demands of the house were simulated using DesignBuilder, a building simulation software based on EnergyPlus. The heating and cooling demands are then used to simulate the behaviour of the HVAC system. According to the NatHERS guidelines [10], the minimum temperature of the house was set at 20°C during daytime and 18°C during night time for winter simulation. For summer simulation the maximum temperature was set at 25°C for the entire day.

Simulation shows the thermal energy demand to meet the NatHERS requirements is relatively low; a result of the effective passive design of the building. The thermal energy demand, dependant on the setpoints chosen by the user, has to be met by the HVAC system. The research aims for this solar-PVT assisted HVAC system are to satisfy demands greater than that simulated for this building.

In this study, a 1D analytical steady-state model of the PVT system was utilized to calculate the thermal output of the system under varying weather conditions and different airflow rates. The thermal model also calculates the temperature of the PV panels, and therefore the electrical output, using the temperature correlation specified by the manufacturer of the panels. The PCM thermal storage unit consists of PlusIce PCM bricks, which placed vertically and spaced to create channels for the air to flow through. A simple analytical model was developed to simulate the heat exchange and outlet temperature based on the following assumptions: 1) The temperature of the PCM remains constant through the entire phase change process; 2) the temperature of the PCM remains constant along the total length of the heat exchanger; and 3) the material used to make the brick has the same thermal conductivity as that of the PCM itself.

The PVT system, PCM unit and the ducting that connects the different units and the ducting that connects to the supplies air diffusers have been mechanically modelled, in order to calculate the power of variable speed fans, which is a function of airflow rate. As the ducted HVAC system in this case consists of a combination of flexible and solid ducts, the accurate modelling of the pressure drop is important, in particular for the flexible duct sections. ASHRAE Fundamentals 2009 [11] has been used as a reference to determine the Pressure Drop Correction Factor (PDCF).

Each working mode is optimised using a cost function which maximises the thermal and/or electrical output of the system compared to the energy consumption of the fan.

5.2. Modes switching strategy

In the simulation, a rule-based strategy is used to determine the operating mode of the HVAC system. This is based on the indoor conditions, the HVAC status (e.g. temperatures of the PVT and PVT, etc.) and the weather conditions.

The operating modes and the mode selection strategy are summarised in Table 1, where *HD* is the house heating or cooling demand, T_{pvt} is the calculated PVT temperature, T_{house} is the average temperature of the house, T_{pcm} is the temperature of the PCM, P_{th} is the heating or cooling that the selected operating mode can provide, *Charge* is the charge level of the PCM unit, *mCharge* is the maximum charge level, which is equal to the total latent heat capacity of the PCM, and *Ts* is the sampling time in hours. The variables are evaluated at each time step *k*.

These operating modes have been described in section 3.2, where they have been divided in conditioning modes and PVT modes. In this simulation, the conditioning modes, including those where the PVT system and the PCM unit are pre-heating or pre-cooling for the normal air conditioning system, are represented with numbers from 1 to 5. The only PVT mode considered is PCM Charging, represented as mode *a*. This information is summarised in Table 1.

Using winter heating as an example if the PVT generation occurs at the same time as the house demand, the preferred operating mode is Direct PVT supply. If the heating generation is sufficient the mode 1 is selected. In the case where the heating demand is higher than the generation the normal air conditioning system is used with the PVT pre-heating the air for the air handling unit – mode 4.

If the house requires heating when the PVT is not generating and the PCM unit is charged, PCM Discharging is selected. Mode 2 is selected if the PCM unit can provide enough heating, otherwise the normal air conditioning system will provide the remaining required heating, selecting mode 5. If none of these two resources are available, Normal Conditioning mode is selected - mode 3.

PCM Charging mode is operated independently, but can only be activated if the PVT system can provide heating to the PCM unit and no conflicting modes are already selected, i.e. PVT Direct

Supply (mode 1 or 4) or PCM Discharging (mode 2 or 5). The summer cooling logic is similar and reversed, as presented in Table 1.

Table 1: Operating modes and logic conditions

Mode #	Mode description	Logic conditions in winter	Logic conditions in summer
0	Off Mode	1) $HD_k = 0$	1) $HD_k = 0$
1	Direct PVT supply	1) $HD_k > 0$ 2) $T_{pvt,k}(\dot{V}) > T_{house,k}$ 3) $P_{th,k}(\dot{V}) \geq HD_k$	1) $HD_k < 0$ 2) $T_{pvt,k}(\dot{V}) < T_{house,k}$ 3) $P_{th,k}(\dot{V}) \leq HD_k$
2	PCM Discharging	1) $HD_k > 0$ 2) $T_{pvt,k}(\dot{V}) \leq T_{house,k}$ 3) $P_{th,k}(\dot{V}) \geq HD_k \wedge Charge_k \geq HD_k \cdot Ts$	1) $HD_k < 0$ 2) $T_{pvt,k}(\dot{V}) \geq T_{house,k}$ 3) $P_{th,k}(\dot{V}) \leq HD_k \wedge Charge_k \leq HD_k \cdot Ts$
3	Normal Conditioning	1) $HD_k > 0$ 2) $T_{pvt,k}(\dot{V}) \leq T_{house,k}$ 3) $P_{th,k}(\dot{V}) \leq 0 \vee P_{th,k}(\dot{V}) < HD_k \vee Charge_k < HD_k \cdot Ts$	1) $HD_k < 0$ 2) $T_{pvt,k}(\dot{V}) \geq T_{house,k}$ 3) $P_{th,k}(\dot{V}) \geq 0 \vee P_{th,k}(\dot{V}) > HD_k \vee Charge_k > HD_k \cdot Ts$
4	Direct PVT supply + Air conditioning	1) $HD_k > 0$ 2) $T_{pvt,k}(\dot{V}) > T_{house,k}$ 3) $P_{th,k}(\dot{V}) < HD_k$	1) $HD_k < 0$ 2) $T_{pvt,k}(\dot{V}) < T_{house,k}$ 3) $P_{th,k}(\dot{V}) > HD_k$
5	PCM Discharging + Air conditioning	1) $HD_k > 0$ 2) $T_{pvt,k}(\dot{V}) \leq T_{house,k}$ 3) $0 < P_{th,k}(\dot{V}) < HD_k \wedge Charge_k \geq HD_k \cdot Ts$	1) $HD_k < 0$ 2) $T_{pvt,k}(\dot{V}) \geq T_{house,k}$ 3) $HD_k < P_{th,k}(\dot{V}) < 0 \wedge Charge_k \leq HD_k \cdot Ts$
a	PCM Charging	1) mode=0 ∧ mode=3 2) $T_{pvt,k}(\dot{V}) \geq T_{pcm,k}$ 3) $Charge_k < mCharge$	1) mode=0 ∧ mode=3 2) $T_{pvt,k}(\dot{V}) \leq T_{pcm,k}$ 3) $Charge_k > -mCharge$

Figure 5 shows the ambient temperature (*Ta*), the global horizontal radiation (*Ghr*), the house demand (*HD*), the operating conditioning mode selected (*Mode*), the PCM Charging mode (*PCMCharging*) (equal to 0 when inactive and set as 5 when active) and the resulting charge level (*Charge*). From this figure, it can be found that the system employed different operating modes to meet the fraction of demand, according to the logics presented in Table 1. This figure also presents the charge level profile of the PCM unit. Over July, the simulated system could supply 128 kWh of heating while the house demand is 206 kWh, achieving an average COP, defined as the ratio of thermal input to the building to electrical power consumption, of 32.5 for mode 1 and mode 4, 37.2 for mode 2 and mode 5, and 24.7 for PCM Charging mode. The overall COP in the heating case was 16.3 without considering the increase in electrical energy generation of the PV panels.

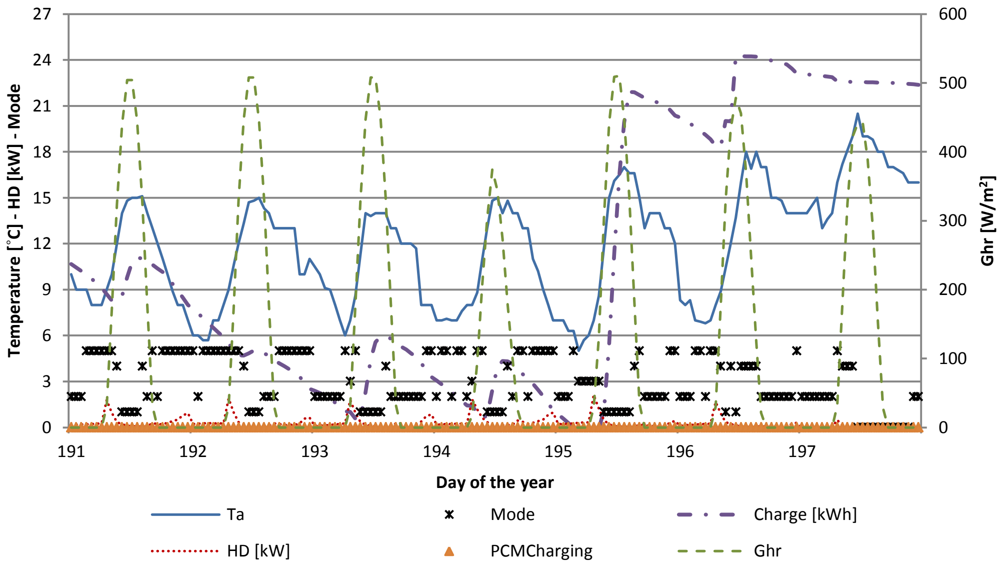


Figure 5: Charge level and operating modes, July, Sydney

Figure 6 presents the results of using the same logical conditions as summarised in Table 1 for cooling case. The house demand and the charge level are presented as positive on the graph for readability purpose, but they were considered negative in the simulation. It can be observed that compared to the winter case, there is more offset between the cooling generation and the demand. Therefore, the system mainly employed mode 2 and mode 5, PCM Discharging mode or PCM Discharging assisted by the air conditioning system. This figure also shows that sometimes the system employed mode 4 - Direct PVT Supply assisted by the air conditioning system at the beginning of the night, when there is no solar radiation but the house is still warm because of its thermal mass. For the remainder of the night, if the PCM unit is not fully charged, the system switched on the PCM Charging mode.

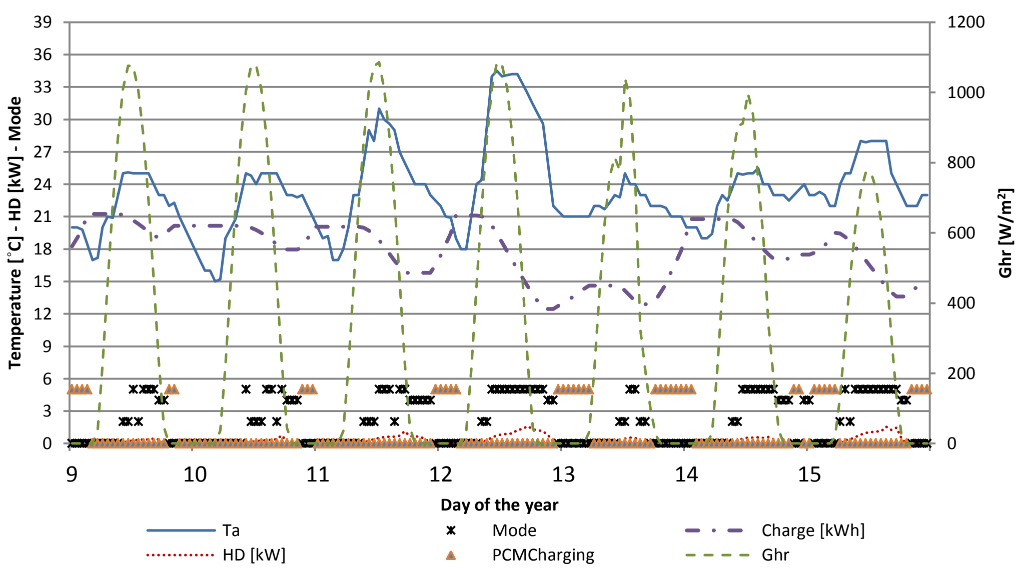


Figure 6: Charge level and operating modes, January, Sydney

Over January, the simulated system could supply 84 kWh of cooling while the demand of the house is 109 kWh, achieving an average COP of 18.3 for mode 1 and mode 4, 22.9 for mode 2 and mode 5 and 21.1 for PCM Charging mode. The overall COP in the heating case was 10.93 without taking into consideration of the increase in electrical energy generation of the PV panels.

6. Conclusions

This paper shows the potential of a solar assisted HVAC system, which includes a PVT system and a PCM thermal storage unit to be able to offset the demand. Even though there are factors and losses not taken into account in this study, this system shows the potential of increasing the efficiency of a standard air-conditioning system significantly. Using air as a working fluid for the entire system helps the integration of the different components into a common ducting system, increasing the reliability and facilitating the maintenance procedure. Having a centralized active PCM thermal storage unit allows the system to store and use the thermal energy only when required and gives the system the flexibility to operate both in winter and summer conditions. Further studies on the best integration of these components have to be undertaken, to manage this system in an optimal way based on the actual weather and system conditions.

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